A Consequence Minimization Approach to Explosive Siting

prepared by

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ABSTRACT

The application of risk-based methodologies for explosive siting is relatively new within the Department of Defense. The usual procedure is to choose the maximum quantity of energetic material which will still meets Inhabited Building Distance (IBD)requirements. A procedure based on consequence minimization has been developed and applied at certain installations. The assumptions behind this methodology are as follows: In the case of an accidental detonation (1) Ground shock will be below perception threshold beyond the station boundary, (2) No debris will fall beyond the station boundary and (3) The probability of window breakage is small. This new procedure is described and a sample problem is examined.

BACKGROUND

The current explosives safety criteria, as defined in DOD Ammunition and Explosives Safety Standards[1], do not define levels of absolute safety; rather, they define a level of acceptable risk. Let us consider the criteria for Inhabited Building Distance (IBD) for Hazard Division (HD) 1.1 materials. In reality, there are two criteria which must be met--an airblast criteria and a frag mentation/debris criteria.

The airblast criteria at IBD for Net Explosive Weights (NEWs) less than 250,000 pounds is given simply as $40W^{1/3}$, corresponding to a pressure level of 1.18 psi. Quoting from the standard:

- (a) Unstrengthened buildings can be expected to sustain damage up to about 5% of the replacement cost.
- (b) Personnel in buildings are provided a high degree of protection from death or serious injury, with injuries that do occur principally being caused by glass breakage and building debris.
- (c) Personnel in the open are not expected to be injured seriously directly by the blast. There could be some personnel injuries caused by fragments and debris, depending largely upon the PES (Potential Explosion Site) structure and amount of ammunition and fragmentation characteristics thereof.

The fragment/debris criteria at IBD is expressed in terms of an acceptable fragment/debris density. Quoting from the standard:

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1994**	2. REPORT TYPE	3. DATES COVERED **00-00-1994 to 00-00-1994**

4. TITLE AND SUBTITLE **A Consequence Minimization Approach to Explosive Siting**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center,Indian Head Division,10901 New Hampshire Avenue,Silver Spring,MD,20903-5640**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM000767. Proceedings of the Twenty-Sixth DoD Explosives Safety Seminar Held in Miami, FL on 16-18 August 1994.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

(1) For populous locations, i.e., those areas and/or functions identified ... above, where military, civilian employees, dependent and/or public personnel are located, the minimum distance shall be that distance at which fragments, including debris from structural elements of the facility or process equipment, shall not exceed a hazardous fragment density of one hazardous fragment per 600 ft^2 ($56m^2$).

A hazardous fragment is defined a fragment having an impact energy of 58 ft-lb (79 joules) or greater.

After examining these criteria, it should be obvious that IBD does not provide azero consequence solution. At IBD, there is a high probability that windows will be broken. In addition, building debris can extend well beyond this distance. Remember, the criteria only states that the hazardous debris density will be less than 1 per 600 ft^2--implying that there will be hazardous debris beyond IBD.

Based on these guidelines, what does Reference 1 give as acceptable quantity-distance requirements? Table 1 provides a synopsis of a portion of the quantity-distance guidance provided therein.

TABLE 1. HD 1.1 QUANTITY-DISTANCE

	DISTANCE IN FEET TO INHABITED BUILDING FROM			
	Earth-Covered Magazine			**Other PES**
NEW (pounds)	**Front**	**Side**	**Rear**	
1	500	250	250	1250
2	500	250	250	1250
5	500	250	250	1250
10	500	250	250	1250
20	500	250	250	1250
30	500	250	250	1250
40	500	250	250	1250
50	500	250	250	1250
100	500	250	250	1250
150	500	250	250	1250
200	700	250	250	1250
300	700	250	250	1250
400	700	250	250	1250
500	1250	1250	1250	1250
700	1250	1250	1250	1250
1000	1250	1250	1250	1250
2000	1250	1250	1250	1250
5000	1250	1250	1250	1250

Let us suppose that for some situations the explosive limits shown in Table 1 were unacceptable. For instance, an installation working with energetic materials that is located in an urban area. If an accident were to occur in such an area, even the consequences allowed by Reference 1 could be devastating. For such an installation, the operative quantity-distance guidance might be expressed as: Choose/set explosive limits for operating buildings and storage areas such that if an accident were to occur, no effects will be experienced beyond the station boundary. Obviously, if such guidance were to be literally interpreted, the only acceptable explosive limit would be zero. However, as will be shown below, the limiting effect of such guidance can be approached.

If an accident were to occur, the effects should be considered: (1) visible dust cloud, (2) ground shock, (3) airblast leading to window breakage, and (4) debris deposition.

<u>Visible Dust Cloud</u>. Any accident will produce visible effects such as a dust cloud. The concentration of explosion products produced by the detonation of confined explosive materials which are contained in the visible dust cloud, are at acceptable levels within a short distance (200-400 feet) of the PES (Potential Explosion Site)[2]. Thus, the presence of a visible dust cloud is considered acceptable.

<u>Ground Shock</u>. Ground shock has been studied in great detail and prediction algorithms are available. The threshold for human perception for ground shock varies with the frequency of the motion. Data indicate that a lower limit for this threshold of about 0.5 in/s is reasonable[3]. This level of motion can occur at relatively long ranges. Therefore, ground motion must be considered when choosing reduced consequence explosive limits.

<u>Airblast/Widow Breakage</u>. No effects beyond the station boundary is interpreted to mean that there is no probability that windows will be broken at the nearest off-station structure as a result of any accident. Window breakage is a probabalistic phenomena. Threshold or incipient window breakage seems to occur at a pressure level of approximately 0.029 psi (200 pascals)[4]. As the pressure increases, the probability of window breakage increases. The relationship between incident pressure level and window breakage probability is taken as a hypergeometric function which has been documented in the literature[4]. Window breakage is also a function of the size of the window and the type of glass employed.

As just indicated, window breakage is a probabalistic phenomena. If the term No Window Breakage is interpreted as a zero probability of breakage and is literally applied, then the explosive quantity allowed is zero, since there is always a finite probability that a window will break. A more reasoned approach is to define and accept a small probability of window breakage.

<u>Debris Deposition</u>. The guidance was interpreted literally in this instance. No accident-produced debris should be deposited beyond the station boundary. Deposition of dust-like debris is considered acceptable.

PROCEDURE

The proposed procedure involves calculations for three phenomena: (1) Ground Shock, (2) Window Breakage, and (3) Debris. Many of the calculations involve an iteration between net explosive weight and

range to obtain an acceptable value for that phenomena. The appropriate Net Explosive Weight is simply the smallest of the three values.

To apply the procedure, the following information is required. The distance from the PES to the nearest station boundary. The type of site; i.e., operating building, earth-covered magazine, exposed storage, etc. If the site is a magazine or operating building, some details as to how it is constructed are needed.

Ground Shock. Figure 1, taken from Reference 3, presents Far-Field Peak Particle Velocity Versus Scaled Distance. Shown on that figure is the scaled distance at which the human perception threshold of 0.5 in/s occurs--74.6 ft/lb$^{1/3}$. Using the distance, R, from the PES to the nearest station boundary, calculate an acceptable charge weight W_{gs}:

$$\mathbf{W_{gs} = (R/74.6)^3}$$

Window Breakage. The first step in the window breakage procedure is to choose an acceptable window breakage probability. This probability should be selected to be low enough to satisfy the intent of the no effects criteria, yet still high enough to allow an acceptable charge weight to be stored.

The second step in the procedure is to assume an NEW and estimate the airblast at the the station boundary. If the PES is an exposed site, then the airblast for a hemispherical surface burst can be used[5]. If the PES is an earth covered magazine (ECM), then the Swisdak equation for an ECM can be used[6]. If the site is neither of these two types, then an appropriate estimate of the airblast must be made. The following equations, taken from References 5 and 6 give the airblast for an exposed site and for an ECM (NOTE: The equation for an ECM has been updated slightly since its publication in Reference 6.):

TABLE 2. AIRBLAST EQUATIONS

EXPOSED SITE	**RANGE**
$P = 6657.5*Z^{(-3.7001+0.2709*(\ln(Z))+0.0733*(\ln(Z))2-0.0127*(\ln(Z))3)}$	Z<60
$P = 226.6*Z^{-1.4066}$	Z>60
EARTH COVERED MAGAZINE	
$P = 67.6879*Z^{(-0.71007-0.11907*\ln(Z))}$	Z>30

For all of the equations shown above, Z is the scaled distance in ft/lb$^{1/3}$ and P is the side-on or incident overpressure in psi.

Once the airblast pressure has been estimated, Figure 2, taken from Reeds work in Reference 4, can be used to determine the breakage probability for this airblast. An iterative procedure between charge weight, airblast, and probability of breakage is then used to determine an appropriate charge weight.

Debris. The DISPRE methodology[7] can be used to estimate the debris range. One of the outputs of MUDEMIMP (one of the computer codes within the DISPRE suite) is the maximum debris range. By iterating on the net explosive weight, a maximum debris range can be computed which satisfies our criteria of zero debris at the station boundary. An important caveat should be noted here. The DISPRE methodology being utilized has not been validated at higher loading densities (charge weight/chamber volume). Thus, an added safety factor of at least 25% should be applied to the charge weight obtained. Once DISPRE has been validated at higher loading densities, this factor can, probably, be removed.

A second, somewhat simpler, approach is as follows. Select a net explosive weight and estimate by any appropriate means a maximum launch velocity which would be produced by the detonation of this amount of energetic material inside the structure. With this maximum launch velocity, use a trajectory program such as TRAJ[8] to compute maximum debris range as a function of debris weight. Iterate on the net explosive weight (initial velocity) until an appropriate maximum debris range is obtained. Figure 3 is a result of a series of trajectory runs; it relates debris weight, launch velocity, and maximum range. This figure assumes several things: (1) the debris is concrete, (2) the debris is in the form of chunky pieces (fragment shape factor, B, has a value of 0.333), and (3) debris roll or ricochet does not occur.

SAMPLE PROBLEM

Consider the following example. A magazine has a currently approved explosive limit of 5,000 pounds of Hazard Division 1.1 material. The magazine is an earth-covered bunker with an internal volume of 1500 ft^3. It is constructed of reinforced concrete (1/2-inch bar with a 12-inch separation) and has nominal dimensions of 17 x 12 x7.5 (L x W x H). Its walls and roof are each 12-inches thick. There is a minimum of 24-inches of soil over the roof and two sides. The distance from the magazine to the nearest part of the station boundary is 850 feet; the distance to the nearest off-station structure, residential housing, is 1600 feet. The structure is located at a site in a suburban area.

According to Table 1, taken from Reference 1, the Explosive Safety Quantity-Distance (ESQD) arc which must be associated with a 5,000-pound NEW is 1,250 feet. Let us assume that the Station Commander wishes to minimize the consequences of the effects of an accident Apply the procedures described above and determine a Reduced Consequence explosive limit.

GROUND SHOCK.

$$W_{gs} = (R/74.6)^3$$

$$W_{gs} = (850/74.6)^3 = 1{,}480 \text{ pounds}$$

WINDOW BREAKAGE

After discussions with the Station Commander, it is decided that an acceptable probability of window breakage is 0.005.

Although, in the strictest sense, the magazine is not an earth-covered magazine, the airblast from the structure can be approximated using the airblast equation for an earth covered magazine.

The breakage probability of 0.005 corresponds to a pressure level of 0.052 psi. Solving the ECM equation shown in Table 2 for the charge weight corresponding to a pressure level of 0.052 at a range of 1600 feet (range to nearest off-station structure) gives a weight of 480 pounds.

DEBRIS. Figure 3 only considers debris weights up to 100 pounds. How common is a 100-pound piece of chunky debris? Do we need to consider even heavier debris? Using techniques developed by Porzel[9] for the NESIP Technology Base, the probability of occurrence of a 100-pound piece of debris can be estimated. Porzel defines a number distribution of the form:

$$\mathbf{N(>L_L) = N_0 exp(-L_L/L_c)}$$

and

$$\mathbf{L_L = (1728 * W_L/(B * P_c))^{1/3}}$$

where

N(>L)	number of pieces of debris with length greater than L
N_0	total number of pieces of debris
L_L	fragment length associated with weight W_L
L_C	fragment characteristic length
B	fragment shape factor--assumed to be 0.333 for chunky fragments
Pc	density of concrete--assumed to be 175 lb/ft^3

Thus, a 100 pound piece of debris corresponds to a piece with an L_L of 14.36 inches. Based on the described construction of the PES, the fragment characteristic length is taken as 3 inches[7,9]. If the number distribution equation given above is re-arranged, the following is obtained:

$$\mathbf{N(>L_L)/N_0 = exp(-L_L/L_c)}$$

The ratio of $N(>L_L)/N_0$ is the probability of occurrence of a piece of debris with a dimension greater than L_L. In our example case this becomes

$$N(>L_L)/N_0 = exp(-14.36/3) = 0.008.$$

A value of 0.008 means that there is a low probability that there would be debris with weights larger than 100 pounds.

The debris velocity produced by detonations inside this example structure were calculated using procedures described in the DDESB Technical Paper 13[7]. For an assumed 480 pound detonation inside the structure, the initial debris velocity is approximately 160 ft/s. Using Figure 3, the maximum range of a 100 pound piece of debris with a velocity of 160 ft/s is 630 feet. Debris with smaller weights would travel to correspondingly smaller distances. This maximum debris range is less than the distance to the station boundary (850 feet). Therefore, we need to increase the NEW and repeat the calculations. As a second iteration, consider an NEW of 540 pounds. This would produce an initial velocity of approximately 200 ft/s. The maximum range of a 100-pound piece of debris with this velocity is 860 feet.

Thus, based on debris, an NEW of 540 pounds should be used. However, we still need to apply a 25% safety factor to this weight. When this is done, the debris range weight becomes 400 pounds. As indicated above, this safety factor could be removed or reduced once the DISPRE model is validated at higher loading densities.

Ground shock gave an NEW of 1,480 pounds. Window breakage gave a value of 480 pounds. Debris gives an NEW of 400 pounds. Therefore, the Reduced Consequences NEW is 400 pounds.

SUMMARY

A procedure has been presented which allows the determination of an allowable net explosive weight while minimizing the consequences which would be produced if that NEW were involved in an explosive accident.

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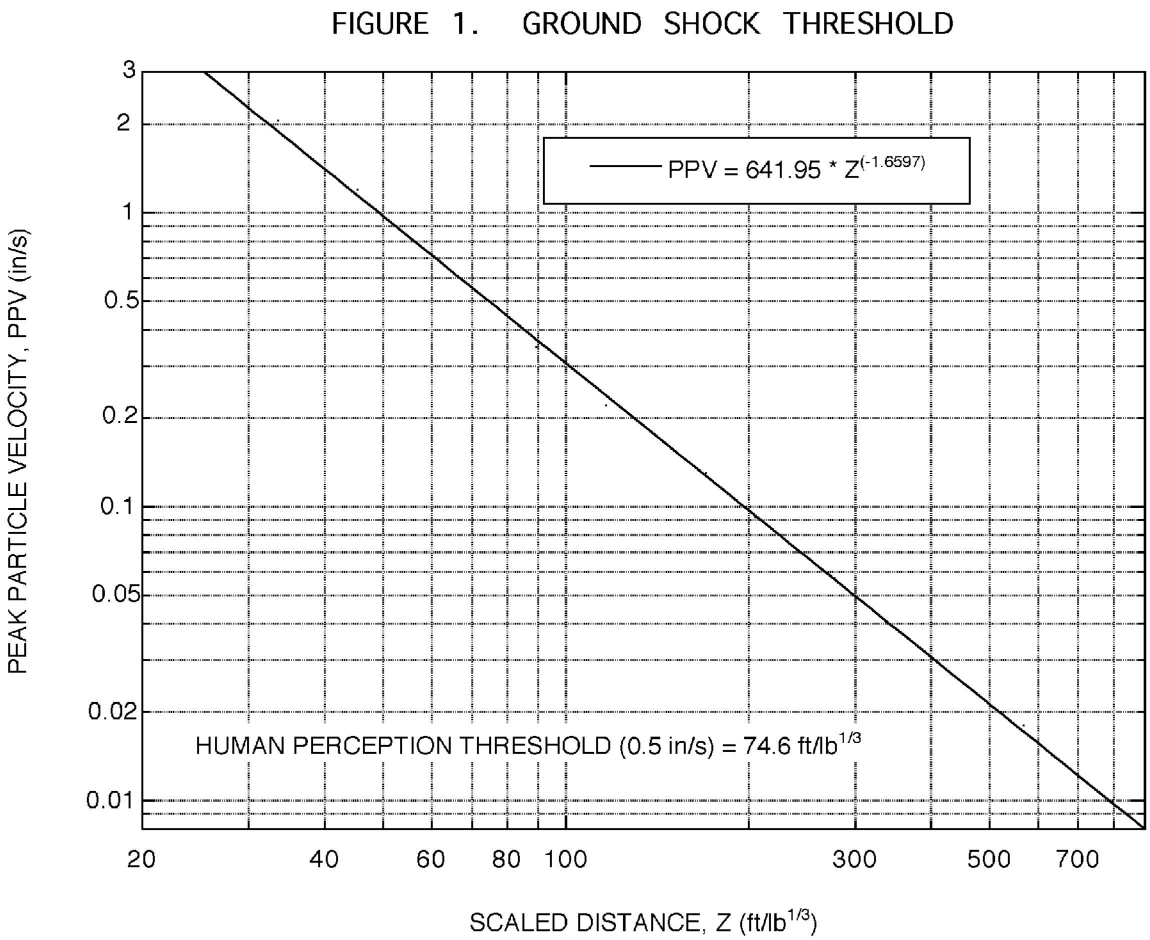

FIGURE 1. GROUND SHOCK THRESHOLD

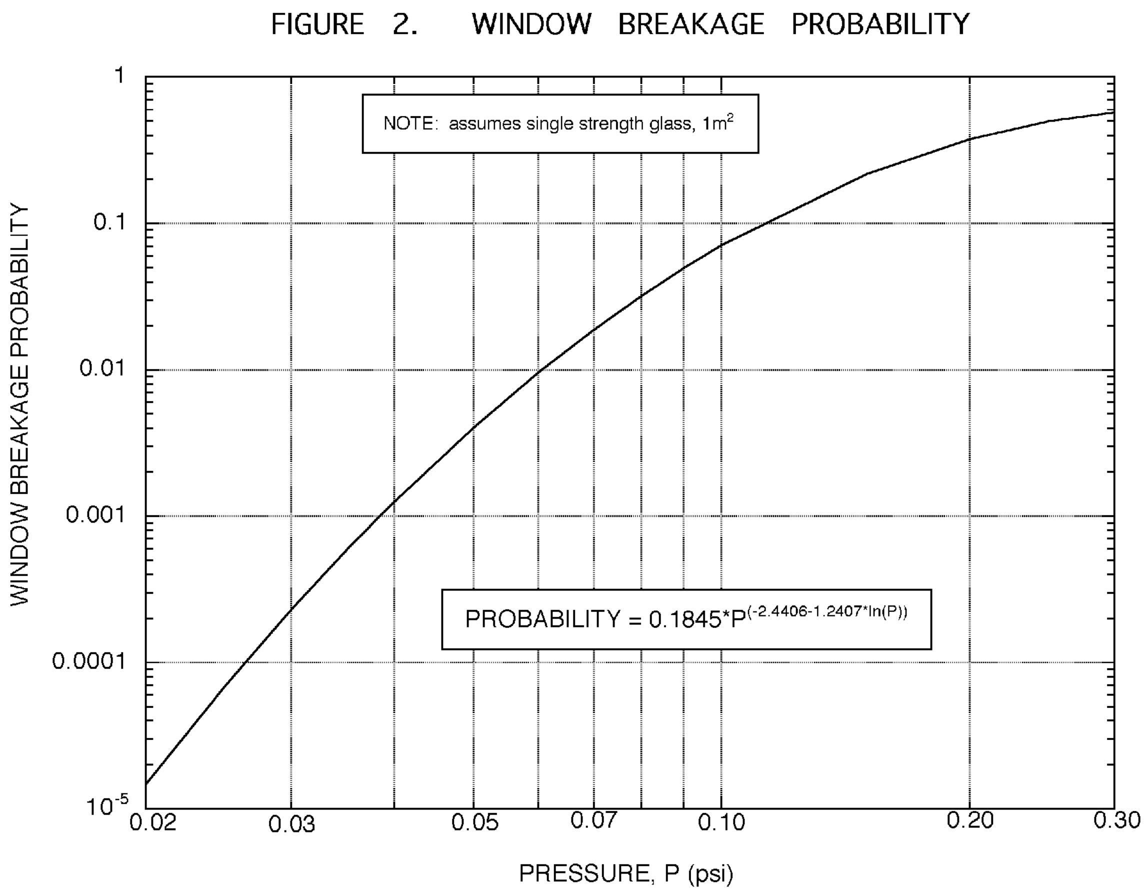

FIGURE 2. WINDOW BREAKAGE PROBABILITY

FIGURE 3A. MAXIMUM DEBRIS RANGE VERSUS DEBRIS WEIGHT-I CHUNKY CONCRETE DEBRIS

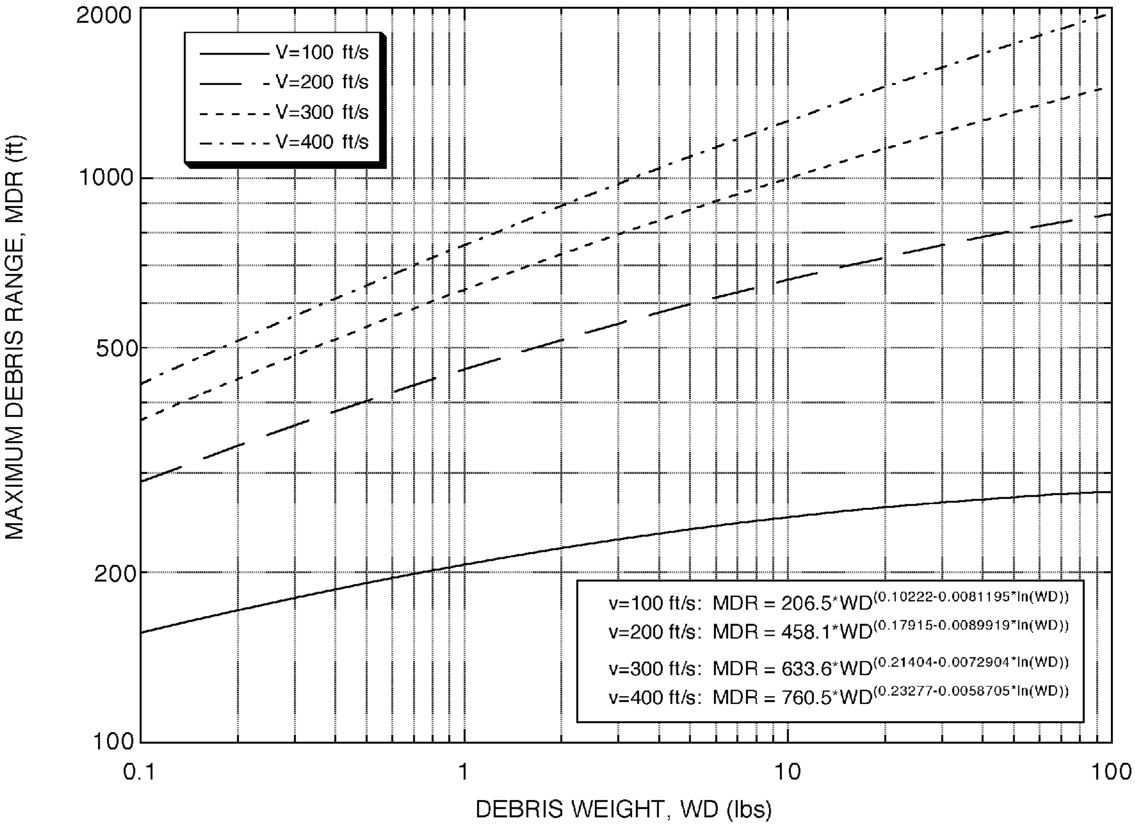

FIGURE 3A.MAXIMUM DEBRIS RANGE VERSUS DEBRIS WEIGHT-1
CHUNKY CONCRETE DEBRIS

FIGURE 3B. MAXIMUM DEBRIS RANGE VERSUS DEBRIS WEIGHT-II
CHUNKY CONCRETE DEBRIS

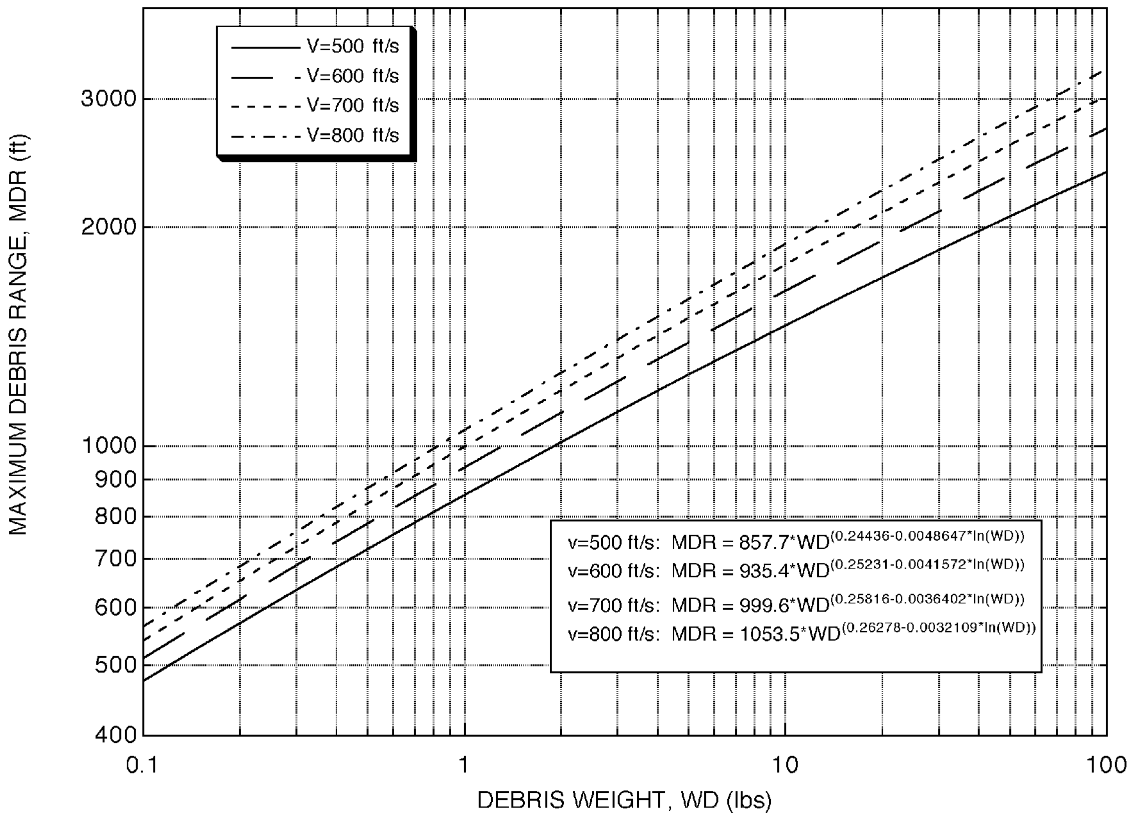

FIGURE 3B.MAXIMUM DEBRIS RANGE VERSUS DEBRIS WEIGHT-1
CHUNKY CONCRETE DEBRIS